

# **Synthetic Aperture Sonar Beam Forming in the Presence of Internal Waves**

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## **LONG-TERM GOALS**

The long-term goal of our research is to incorporate environmental estimation and compensation methods into the synthetic aperture sonar (SAS) image formation process. Specifically, our goal is to mitigate shallow water environmental effects that result in degradation of image resolution through space/time variations in the sound speed field, e.g., internal waves, turbulence, bathymetry.

## **OBJECTIVES**

The current focus of our research is to develop an algorithm to compensate for linear internal wave effects during the formation of a synthetic aperture in a shallow water environment. Internal waves impact the propagation of the acoustic signal and consequently the phase by changing the space-time structure of the sound speed field. Our intent is to model the phase change due to internal waves, with the challenge of developing a methodology to remove the internal wave induced phase variation as part of the formation of the synthetic aperture.

Our research objectives are consistent with the ONR concept of Synthetic Aperture Sonar at Far Ranges and Severe Sites (SASAFRASS) and the goals of the SAS PRIMER experiment, which is affiliated with the Coastal and Mixing Optics Experiment conducted during 1996, [1] [[2]. The intent of the SASAFRASS concept is to increase SAS imaging performance under conditions where environmental propagation effects are significant sources of blurring. The experimental emphasis of SAS PRIMER is on high frequency acoustic propagation through shallow water internal waves.

## **APPROACH**

One facet of our approach relies on using a simulation to provide synthetic data to aid in the development of a simple forward model. The simulation produces a phase history of a point target in the presence of an internal wave field, with initial emphasis on linear internal waves [3] and [4]. The simulation uses the Gaussian Beam formulation of ray theory and generates a realization of a sound speed field perturbed by linear shallow water internal waves through which the rays propagate [5].

We intend on embedding the forward model in a beam formation algorithm. The forward model consists of a simplified Gaussian beam ray trace formulation with a depth dependent sound speed profile as the zeroth order unperturbed propagation model, and a Rytov approximation to include

internal wave effects as a phase perturbation. In past efforts we first tested the concepts using time of arrival series, sensor navigation and angle of arrival series along the synthetic aperture as the synthetic data from which the forward model parameters are estimated [3][4]. Our current objectives are to reformulate the algorithms such that they are applicable to in-phase and quadrature (I&Q) stave data.

We are continuing to assess the impact of linear internal waves on SAS by using the data collection by the DARPA/Raytheon SAS system at Lake Washington to estimate the potential blurring internal waves could cause in such an environment [6]. We plan on using the in situ measurements of sound speed and temperature to inject internal waves into the environment and test the effects on the Wavenumber Imaging algorithm typically used in SAS processing [7].

Another issue we intend on examining is the affect of bottom bounce on the coherence across a synthetic aperture. Currently we plan on analyzing the SAS PRIMER tower data that contains bottom bounces and making a comparison with direct path data to explore the impact on aperture coherence.

## WORK COMPLETED

Developed a forward model to estimate environmental model parameters from I&Q derived data.

Initial assessment of potential internal wave blurring on SAS for Lake Washington using simulation.

## RESULTS

The approach we are taking is to express the imaging forward model in the form of a surface integral over the bottom similar to a Kirchhoff integral used in seismic migration processing [8],[9]. The forward model of the received pressure is given by

$$\tilde{P}(\bar{r}_h, \bar{r}_p, t) = \int_{bottom} ds(\bar{r}') \left\{ -\frac{\partial}{\partial t} H(\bar{r}', \bar{r}_h, \bar{r}_p, t) \right\} \eta(\bar{r}')$$

where the integral is over the illuminated bottom area,  $\eta(\bar{r})$  is the bottom reflectivity,  $\bar{r}_p$ ,  $\bar{r}_h$  are the locations of the sonar projector and hydrophone receiver respectively. The imaging kernel function is

$$H(\bar{r}', \bar{r}_h, \bar{r}_p, t) = \int d\omega \tilde{p}_{inc}(\omega) e^{-i\omega t} \sum_{m,m'} A_{m,proj} A_{m',rec} \left\{ \frac{\hat{n} \cdot \hat{t}_m}{c_m} + \frac{\hat{n} \cdot \hat{t}_{m'}}{c_{m'}} \right\} \tilde{G}_m \tilde{G}_{m'} e^{i\phi_m(\omega, \bar{r}) + i\phi_{m'}(\omega, \bar{r})}$$

where the summations over  $m, m'$  represent the multipath contributions. The symbols  $\tilde{p}(\omega)$  is the incident waveform,  $A_{m,proj}$ ,  $A_{m,rec}$  are the receiver and projector aperture functions,  $\tilde{G}_m$  is the propagation amplitude and  $\phi_m$  is the phase for the  $m$ th multipath,  $\hat{n}$  is a normal unit vector to the surface,  $\hat{t}_m$  is a unit vector along the ray for the  $m$ th multipath at the bottom and  $c_m$  is the sound speed at the bottom for the  $m$ th multipath. The phase consists of a sum of an unperturbed phase contribution from a reference model with a depth dependent only sound speed profile, and a perturbation arising from internal waves. The reference sound speed profile is constructed using a set of empirical orthogonal functions with coefficients as parameters [10]. The coefficients will be estimated from data using a procedure that will be developed at a later date. We assume internal wave effects are small enough to allow the use of unperturbed ray paths to calculate the phase perturbation.

We have performed preliminary simulations for the Lake Washington data collection to examine the potential blurring by internal waves in such an environment. During the experiment only a limited amount of in situ data was collected with no instrumentation to assess directly the internal wave activity. The processed SAS results indicate a minimum of environmental degradation [6]. We have simulated the results using the available temperature and sound speed profiles. Shown in Figure 1 is a sound speed profile and example eigenray paths between the sensor at a depth of 30m and a target on the bottom at a 55m depth 1 km away in ground range. The assumed sensor parameters are: 50 kHz center frequency, 10 kHz bandwidth. The sound speed is downward refracting and the eigenray paths we have used in the simulation involve a bottom bounce with no surface interactions, an example is highlighted in Figure 1b. In Figure 2 are topographic displays of the SAS point response function for various environmental conditions ranging from a constant sound speed to refraction with internal waves. We have used only one eigenray series in the calculations and held the propagation amplitude constant so as to examine the phase perturbations. The data is processed such that a 10 cm azimuth resolution is obtainable for a constant sound speed profile of 1500 m/s. No autofocus techniques are used in the processing. As seen from the figures the dominant environmental complexity arises from the downward refracting character of the sound speed profile. The internal waves have a reduced impact due to the localization near the thermocline at a 10m depth and having the eigenray path spend minimal time near the thermocline region. Alternative paths and sensor depths could result in increased significance in the internal wave effects. Shown in Figure 3 are corresponding contour plots of the point response functions with 5 dB increments for the constant sound speed and refractive case. The resolution loss is apparent when comparing the constant sound speed case with the refractive calculation. The range location of the target is larger for the refractive case because of the longer travel time and the constant sound speed assumption used in the Wavenumber processor.

## **IMPACT/APPLICATION**

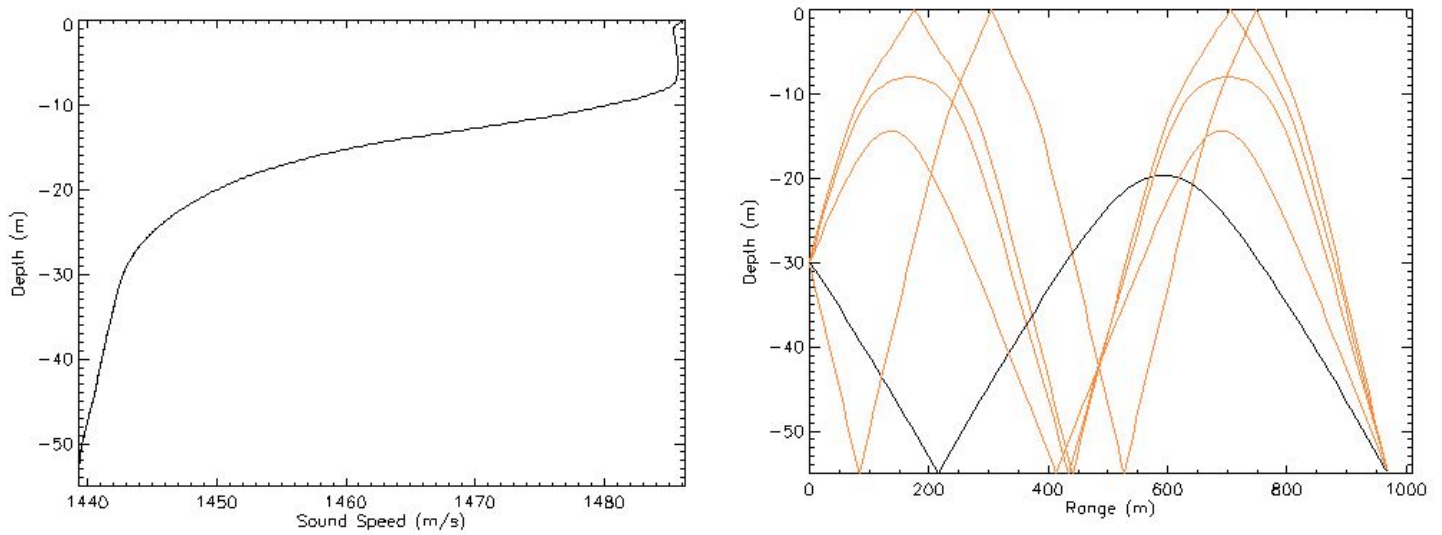
The development of a compensation scheme for environmental effects is important for the situations when moderately high frequency sonar is working at longer stand off ranges that require increased resolution for the detection and classification of objects lying on the bottom. Continuing development of a compensation scheme can lead to improved beam formation algorithms with increased resolutions and with environmentally adaptive capabilities to estimate and mitigate the defocusing effects associated with internal waves, refraction and multipath returns.

## **TRANSITIONS**

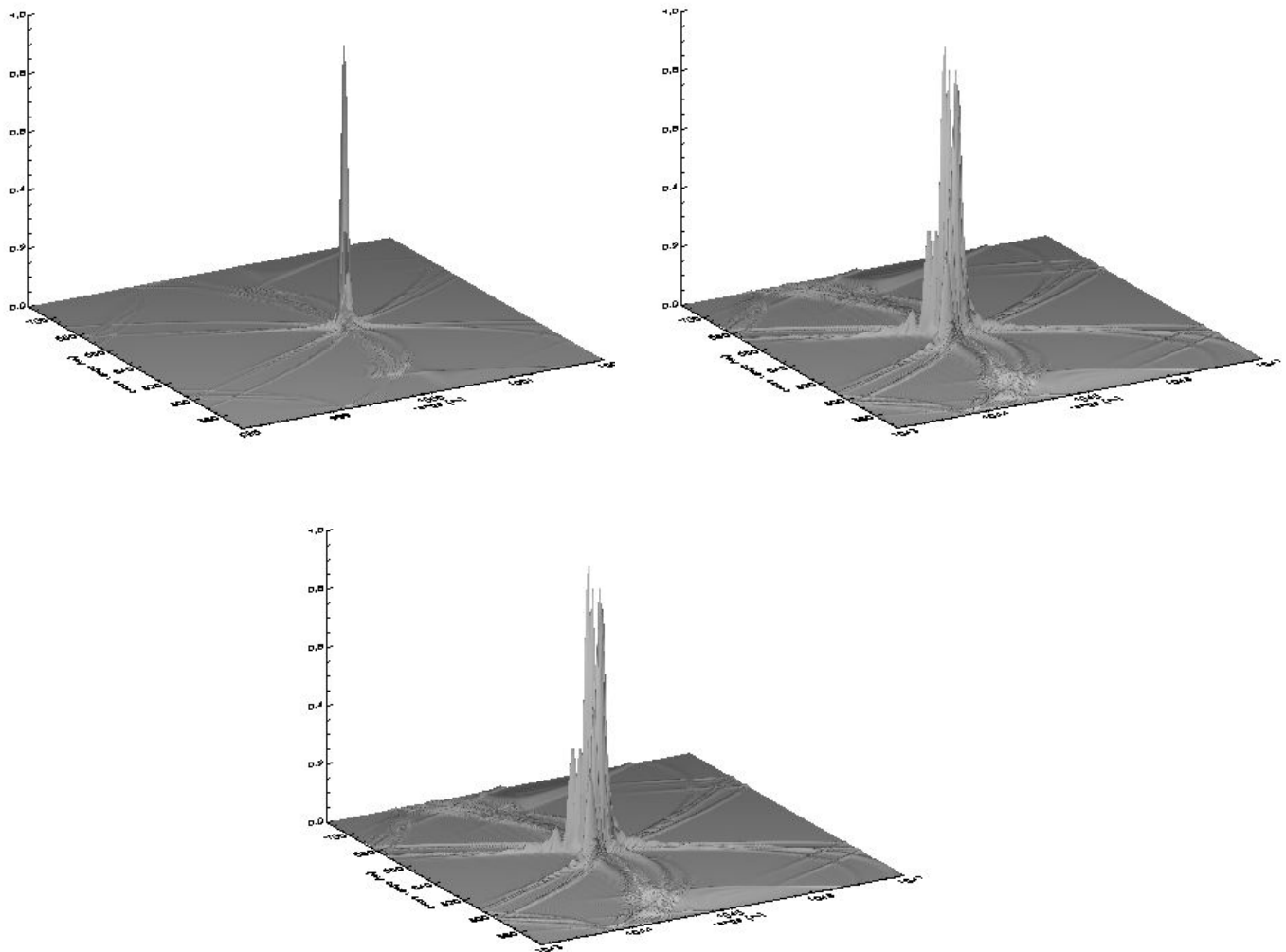
There are currently no actions being taken to transition the results of this work to other projects

## **RELATED PROJECTS**

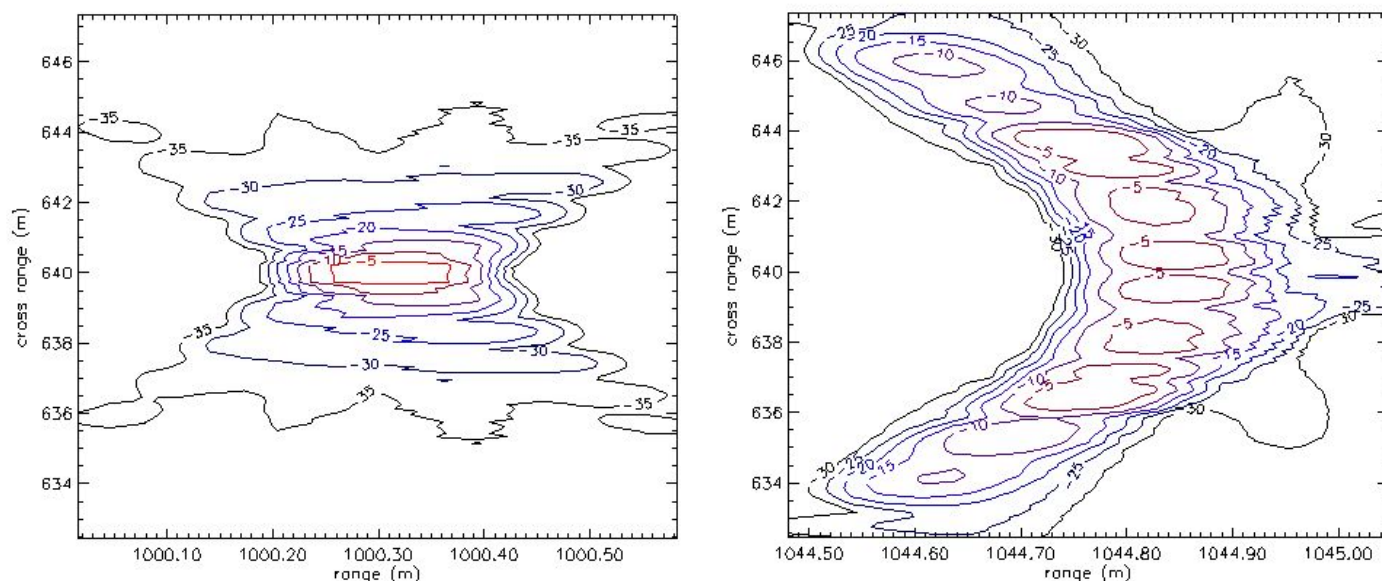
- 1) The shallow water internal wave characterization being done by Murray Levine at OSU [11],[12]
- 2) The analysis of SAS PRIMER acoustic data by UW/APL to determine the impact of internal waves on beam formation across an array of hydrophones on a tower, and on acoustic wave propagation
- 3) Analysis of data collected by the DARPA/Raytheon SAS system and the Hi/Low frequency SAS system at the Coastal Systems Stations Naval Laboratory in Panama City Fl.



**Figure 1 (a) Lake Washington sound speed profile for August 23, 1996. (b) Potential eigenrays propagating to a bottom target at a range of 1000m. Highlighted eigenray used in point response function.**



**Figure 2 (a) Point response function for ideal constant sound speed profile with linear eigenrays. (b) Lake Washington point response function using bottom bouncing eigenray in Figure 1. (c) Lake Washington point response function with internal wave effects.**



**Figure 3 Contour plot of SAS point response functions in decibels with 5dB increments.**  
**(a) Constant sound speed profile case. (b) Refractive case with depth dependent only sound speed profile.**

## REFERENCES

- 1 Workshop sponsored by the Office of Naval Research on "The Future Directions for Synthetic Aperture Sonar," November 10-11, 1998, Coastal Systems Station Naval Laboratory, Panama City Fl
- 2 a) F.S. Henyey, J.M. Grochocinski, S.A. Reynolds, D.Rouseff, "Pre experiment modeling: Effects of internal waves and turbulence on a synthetic aperture sonar (SAS)," Applied Physics laboratory, Seattle, WA, Rep.  
 b) F.S. Henyey, D. Rouseff, J.M. Grochocinski, S.A. Reynolds, K.L. Williams, T.E. Ewart, "Effects of Internal Waves and Turbulence on a Horizontal Aperture Sonar," IEEE J. Oceanic Eng., Vol.22, No.2, April 1997
- 3 Johnson, L.V., J. Eisenberg, L. Abdelahad, J. Coxwell, "Synthetic Aperture Sonar Beam Forming in the Presence of Linear Shallow Water Internal Waves," Arete' Associates Report, ARW-99-586-001-TR, February 9, 1999
- 4 Johnson, L.V., J. Eisenberg, J. Goldberg, "Synthetic Aperture Sonar Beam Forming in the Presence of Linear Shallow Water Internal Waves Final Report," Arete' Associates Report, ARW-00-503-002-TR, April, 2000

- 5 M.B. Porter, H.P. Bucker, "Gaussian beam tracing for computing ocean acoustic fields," J.Acoust.Soc.Am. 82, 1349-1359 (1987)
- 6 Garrood, D., N. Lehtomaki, T. Luk, M. Neudorfer, A. Palowitch, "Synthetic Aperture Sonar: An Evolving Technology," Sea Technology, vol. 40, no. 6, June 1999
- 7 Peter T. Gough and David W. Hawkins, "Unified Framework for Modern Synthetic Aperture Imaging Algorithms," The International Journal of Imaging Systems and Technology, vol. 8, no. 4, pp. 343-358, (1997).
- 8 Berkhout, A.J., "Seismic Migration Imaging of Acoustic Energy by Wave Field Extrapolation, A. Theoretical Aspects," 3<sup>rd</sup> Edition, ELSEVIER Pub. 1985
- 9 Zhu, T., "Ray-Kirchhoff migration in inhomogeneous media," Geophysics, Vol. 53, No. 6, June 1988, pp. 760-68
- 10 A. Tolstoy, O. Diachok and L.N. Frazer, "Acoustic Tomography Via Matched Field Processing," J. Acoust. Soc. Am. 89 (3), pp. 1119-1127, Mar. 1991.
- 11 Private communications with Murray Levine
- 12 T. Boyd, M.D. Levine, S.R. Gard, "Mooring Observations from the Mid-Atlantic Bight, July-September 1996," Oregon State University Report, Data Report 164, Reference 97-2